Optimal networked controllers for networked plants

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ABSTRACT

In this thesis, we study networked systems composed of discrete-time systems interacting over discrete-time networks. These systems are emerging in many application areas and require new distributed control and estimation design methodologies. Most existing approaches represent networked system models by structured system models (systems with structured state-space or input-output representations) assuming a complete equivalence between the two models. In this thesis, we carefully analyze the connection between these two models and study the conditions under which networked systems can be viewed as structured systems, and vice versa. Although, networked systems are shown to be equivalent to structured systems in general, we show that modeling the networked systems as systems with structured transfer function matrices is inappropriate for problems which require stabilizability and detectability of the designed networked system. This is due to the lack of constructive proofs in literature to obtain a stabilizable and detectable networked system corresponding to an unstable structured transfer function matrix. This important observation shows that the theory developed for designing distributed controllers using transfer function approaches (where the designed transfer functions can in general be unstable) may not provide a stabilizing networked controller.

We refer to the property of realizing a structured transfer function matrix as a stabilizable and detectable networked system by *network realizability*. Although this problem is mostly open and appears to be difficult, we partially answer this problem by providing a constructive proof to show that stable structured transfer function matrices are always network realizable.

Based on this development, we consider the problem of designing stabilizing networked controllers for a given networked plant. As transfer function approaches are not suitable, we develop a state-space approach using classical Youla-Kčera parameterization techniques to parameterize all internally stabilizing networked controllers for the given networked plant. This formulation allows us to pose the problem of finding stabilizing networked controllers as an unconstrained convex optimization problem, which can be

solved using standard techniques. This formulation allows us to solve the optimal networked $\mathcal{H}_2$ and $\mathcal{H}_\infty$ control problems while ensuring that the solution is a stabilizing networked controller that can be implemented as sub-systems interacting over the given network.

It turns out that the optimal stabilizing networked controllers can have a large order as they trade off complexity for the lack of complete communication graph. The optimal solutions provide performance limitations of the controllers when constrained to be networked. In order to obtain networked controllers with order comparable to that of the networked plant, we provide a methodology to obtain full-order internally stabilizing networked controllers using linear matrix inequalities. This methodology being based on a sufficiency condition, assures only sub-optimal full-order stabilizing networked controllers.

Finally, we consider the problem of designing a networked estimator for a given networked plant. Then, we express this problem as a networked control problem for an equivalent plant model and apply our networked controller design approach. We provide the parameterization of all stable networked estimators and the networked estimation problem is expressed as an unconstrained convex optimization problem that can be solved using standard techniques.

We conclude the thesis with a look at future research directions - the development of model reduction techniques for networked systems, the development of distributed design methods, and the extension of our design methodology to include network model uncertainties and other distributed performance objectives.